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Methodology to Size an Optimal Stand-Alone PV/wind/diesel/battery System Minimizing the Levelized cost of Energy and the CO_2 Emissions

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Abstract

The objective of this paper is to propose a methodology for designing a stand-alone hybrid PV/wind/diesel/battery minimizing the Levelized Cost of Energy (LCE) and the CO_2 emission using genetic algorithm. The methodology developed was applied using solar radiation, temperature and wind speed data, collected on the site of Gandon, located in the northwestern of Senegal. Obtained results were presented as optimal Pareto front. The optimal number of devices, the Levelized Cost of Energy (LCE) and the CO_2 emission were determined for each solution. An influence study of the size of diesel generator on the optimal configuration was carried.

Keywords: hybrid system, optimization, genetic algorithm;

1. Introduction

In remote regions, electric energy is usually supplied by diesel generators. In the most cases, supplying demand energy using diesel fuel is so expensive and increases the amount of CO_2 emitted. Thus, the hybrid system (PV/wind/diesel/battery) becomes competitive with the only diesel generator [1]. Further, the use of a single renewable energy source such as wind or solar energy is inadequate to meet the demand for long periods due to the high cost of system as well as storage subsystem [2–3].

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To meet this challenge, the renewable sources such as wind and solar energy can be used in combination with the conventional energy system making hybrid PV/wind/diesel/battery systems.

Several methodologies have been developed in this sense. The works [4-6] have used an iterative method of optimization to minimize the Annualized Cost of System (ACS). These methods have allowed studying the optimization of a hybrid system.[7-9] have studied the performance of hybrid systems using genetic algorithm by minimizing the only cost of system. They did not take into a count other objective (like the Loss of Power Supply Probability (LPSP) or the CO2 emission) to minimize. Moreover, methods outlined in these works did not take into account all devices of system such as wind turbine, PV module, regulator, battery, inverter and diesel generator. In the work [10], authors have designed and optimized hybrid PV/wind/battery systems minimizing the Annualized Cost of System (ACS) and the Loss of Power Supply Probability (LPSP). In that work, the authors did not take into account the diesel generator, which can help to make the hybrid PV/wind/diesel/ battery system more economic than the use of the only PV/wind/battery system. Also, the CO2 emission was not evaluated in that work. So, the contribution of this paper is to propose a methodology for designing optimal PV/Wind/diesel/battery systems minimizing the Levelized Cost of Energy (LCE) and the CO_2 emitted. The methodology developed in this work was applied using the solar radiation, the temperature and the wind speed collected in the site of Gandon located in the northwestern coast of Senegal. Further, the study of influence of the diesel generator on the optimal configuration will be done. The decision variables included in the optimization process are the number of PV modules, the number of wind turbines, the number of batteries, the number of solar regulators, the number of inverters and the number of diesel generators.

2. Model of the hybrid system components

Hybrid solar-wind-diesel power generation system coupled to battery bank consists of a PV module, a wind turbine, a diesel generator, a solar regulator a battery bank, and an inverter. A schematic diagram of the basic hybrid system is shown in Fig 1. The PV module and the wind turbine work together to meet the load demand. When the renewable energy sources are sufficient, the generated power, after meeting the load demand, provides energy to the battery abnk up to its full charge. The battery supplies energy demand to help the system to cover the load requirements, when energy from renewable emery is inferior to the load demand. The load will be supplied by diesel generators whether power generation by both wind turbine and PV array is insufficient and the storage is depleted.

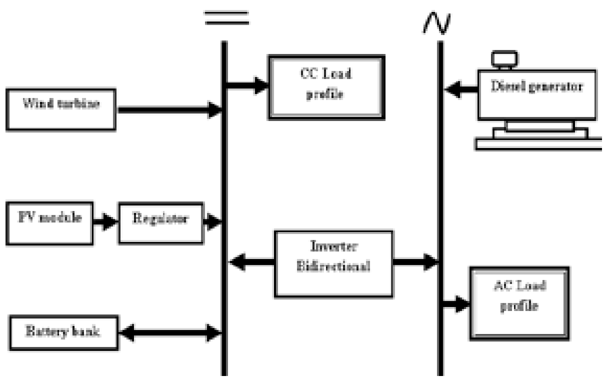

Fig.1. Bloc diagram of the hybrid solar-wind-diesel system

3. Methodology

In this paper, the Levelized Cost of consumed Energy (LCE) was considered. We do not consider the cost of the energy generating because in the remote village, most of the energy generated was lost. For example, if the PV generator or wind turbine generator produces energy during an hour when the electrical load is zero and the batteries are fully charged, then the energy produced by the PV generator or wind turbine generator was lost. In addition, the energy is also lost in the charge and discharge processes of the batteries.

3.1. Mathematical model of PV module

The photovoltaic module performance is highly affected by the solar irradiance and the PV module temperature. In this paper, a simplified simulation model is used to estimate the PV module performance. To estimate the PV module output, the solar radiation available on the module surface, the ambient temperature and the manufacture data for the PV module (Table.1) was used as model inputs. The calculation method is given by Eq.1.

$$P_{pv} = V_{oc} \cdot I_{sc} \cdot FF \tag{1}$$

Where: I_{sc} (A) and V_{oc} (B) are the short circuit current and open circuit voltage of a solar photovoltaic module [11], FF (dimensionless) is the fill factor. It is the ratio between the nominal and maximum power standard [12].

3.2. Mathematical model of Wind turbine

The average output power from a wind turbine is the power produced at each wind speed multiplied by the frequencies of the wind speed, integrated over all possible wind speeds [13]. Eq.2 gives the average of the output power from a wind turbine.

$$P_{wa} = P_r \cdot \left\{ \frac{\exp\left[-\left(\frac{v_{cin}}{A}\right)^k\right] - \exp\left[-\left(\frac{v_r}{A}\right)^k\right]}{\left(\frac{v_r}{A}\right)^k - \left(\frac{v_{cin}}{A}\right)^k} - \exp\left[-\left(\frac{v_{cou}}{A}\right)^k\right] \right\} \tag{2}$$

Where, A (m/s) is scale parameter, k is shape parameter (dimensionless), v is the wind speed (m/s), v_{cin}, v_r and v_{cou} are the cut-in speed, rated speed and cut-off speed given in (m/s). A plot of P_w versus v is shown in Fig.2.

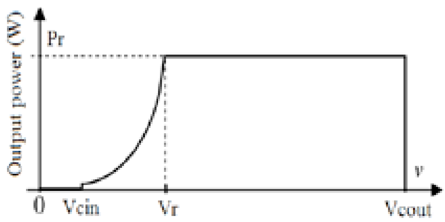

Fig. 2. Power curve of a wind turbine

The total output power of the two generators (wind turbine and PV module) is given by Eq.3:

$$PT = N_{pv} \cdot P_{pv} + N_{ag} \cdot P_{wa} \tag{3}$$

Where N_{pv} and N_{ag} are the total number of the PV modules and the wind turbines respectively.

3.3. Mathematical model of regulator

The solar regulator is the device charged to monitor the battery charge and discharge. It is dimensioned according to its input current, given by the Eq.4:

$$I_{rg} = \frac{N_{pv} \cdot P_{pv}}{N_{pvs} \cdot n_{rg} \cdot U} \tag{4}$$

Where N_{pv} is the total number of PV modules, N_{pvs} is the PV modules number in series, η_{rg} (%) is the efficiency of the regulator and U (V) is the nominal system operating voltage.

3.4. Mathematical model of diesel generator

The diesel generator is the device of system used to supply the load when the power generation by both wind turbines and PV module is inadequate and the storage is depleted. The diesel generator model is designed in such a way that the diesel generator is always operating between 30 and 100% of their nominal power [8]. Energy generated by diesel generator in an hour t is defined by the Eq.5:

$$P_{OG} = P_{NG} \cdot N_{dg} \cdot \eta_{Gr} \tag{5}$$

Where P_{NG} (kW) is the nominal power of diesel generators, N_{dg} is the total number of the diesel generators P_{OG} is the output power from diesel generators and η_G is the efficiency of diesel generators. In this study, it is assumed that the diesel generator lifetime is 7 000 h, and its minimum output power is 30%.

3.5. Mathematical model of Inverter

The inverter is the device of power electronics which allows converting the DC current from DC bus bar to the AC current for AC loads. The power transiting the inverter to serve the demand is given by Eq.6:

$$P_{in} = \frac{P_{ch}}{n_{in}} \tag{6}$$

n_{in} is the inverter efficiency specified by the manufacturer (%), P_{ch} is the hourly demand (W).

3.6. Mathematical model of battery bank

If the energy produced by the wind farm and the PV module generator is greater than the load then the surplus will be stored in the batteries. When power generation is not able to satisfy load requirements, energy will be extracted from the battery bank. The load will be supplied by the diesel generators when power generation by both wind turbine and PV generator is not enough and the storage system is depleted. The battery nominal capacity is modeled by using Eq.7 [14]:

$$\varphi_r = \frac{N_{bt}}{N_{bs}} \cdot \varphi_{bt} \tag{7}$$

Where N_{bt} is the batteries total number, N_{bs} is the batteries number in series, φ_{bt} is the unit nominal capacity (Ah) of a battery.

For a good knowledge of the real state of charge (SOC) of a battery, it is necessary to know the initial SOC, the charge or discharge time and the current. However, most storage systems are not ideal, losses occur during charging and discharging and also during storing periods [15]. The state of charge of the battery bank was calculated according to the model given in the reference [15].

The minimum state of charge of the battery bank (SOC_{min}) can be expressed as Eq.8:

$$SOC_{\min} = (1 - DOD) \cdot SOC_r \tag{8}$$

Were DOD (%) is the depth of discharge and SOC_r is the rated state of charge of battery bank. In our case, the DOD assumed equal to 60%. So, the minimum state of charge (SOC_{min}) that the battery bank can reach is 40% of the state of charge nominal (SOC_r).

The input/output battery bank power $P_{bt}(t)$ can be computed according to the following strategy:

- If $PT(t) = \frac{P_{ch}(t)}{n_{ond}}$, then, all produced energy is consumed by the demand. So, $P_b(t)=0$
- If $PT(t) > \frac{P_{ch}(t)}{n_{ond}}$, then, the surplus of power $P_b(t) = PT(t) - \frac{P_{ch}(t)}{n_{ond}}$ is used to charge the battery bank, and no storage energy was loosed.
- if $PT(t) < \frac{P_{ch}(t)}{n_{ond}}$, then the lack of power $P_b(t) = PT(t) - \frac{P_{ch}(t)}{n_{ond}}$ is provided by the battery bank up to SOC_{min}.
- if $PT(t) < \frac{P_{ch}(t)}{n_{ond}}$ and the battery bank are depleted ($SOC=SOC_{min}$) or the energy providing from the battery bank is not enough to supply the load, then the diesel generators supply needed by the load and the surplus energy (if any), is used to charge the battery bank [16].

4. Objective functions

The objective function to minimize is the Levelized Cost of the consumed Energy (LCE) and the pollutant emission (kg CO2) which is the main cause of the greenhouse effect.

4.1. Economic model based on LCE concept

The optimal combination of a hybrid solar-wind-diesel-battery system makes the best compromise between the system pollutant emission and the cost of energy. According to the studied hybrid solar-wind-diesel-battery system, Levelized Cost of Energy (LCE) is composed of the levelized capital cost of Energy C_{acap}, levelized maintenance and operation cost of Energy C_{amain} and the levelized replacement cost of Energy C_{arep}.

The Levelized Cost of Energy LCE (€/kWh) is defined by Eq.9:

$$LCE = \frac{J(x)}{Eannual} \tag{9}$$

J(x) is the Levelized Cost of system given by Eq.10:

$$J(x) = C_{acap}(x) + C_{amain}(x) + C_{arep}(x) \tag{10}$$

E_{annual} is the annual consumed energy (kWh/year), x =[N_{pv},N_{ag},N_{dg},N_{rg},N_{bt}, N_{inv}] is the variables decision vector.

Where N_{pv}, N_{ag}, N_{dg}, N_{bt}, N_{rg}, N_{in} are the numbers of PV module, wind turbine, diesel generators, batteries, solar regulators and inverters.

C_{acap}, C_{amain} and C_{arap} are the levelized capital cost, levelized maintenance and the levelized replacement cost of the system.

4.2. Pollutant emissions

The parameter considered in this paper to measure the pollutant emission is the kg of CO_2. It represents the large percentage of the emission of fuel combustion [17]. Further, CO_2 represents the main cause of the greenhouse effect. So we evaluate the amount of the CO_2 produced by the use of diesel generator in the hybrid PV/wind/ diesel/battery system during one year of operation.

The fuel consumption of the diesel generator depends on the output power. It can be given by Eq.12:

$$Cons = B \cdot P_{NG} + A \cdot P_{OG} \tag{12}$$

A=0.246 l/kWh and B=0.08145 l/kWh are the coefficient of the consumption curve, defined by the user [18]. The factor considered, in this work, to assess the emission of CO_2 was 3.15 kgCO2/l [19].

5. Application of the developed methodology

5.1. System optimization model using Multi-Objectives Genetic Algorithm

The objectives to minimize are the Levelized Cost of Energy (LCE) and the CO_2 emission. These objectives are antagonist. So, it is very necessary to find an efficient way to solve that Multi-Objective problem which parameters are also independent.

The Multi-Objective Genetic Algorithm, which has the important characteristics of the concept of optimal Pareto front [20], can be used to solve that kind of problem.

In the case of this study, the objective function was implemented employing genetic algorithm (GA) developed by Leyland and Molyneaux [21, 22]. This tool was designed for the optimization of the engineering energy systems, that are generally non-linear, and uses a statistical technique of grouping of the individual basis on the independent variable (creation of the families which evolves in independent manner). This method has the advantage of maintaining the diversity of the population and of making coverage the algorithm towards optima even difficult to find [23].

The PV output energy and the wind turbine output energy are calculated according to the PV module and the Wind turbine system model by using the specifications of the PV module and the wind turbine. The battery bank with the total nominal capacity φ_r is permitted to discharge up to a limit defined by the minimum state of charge.

The initial assumption of system configuration will be a subject to the following inequalities constraints (Eq 13):

$$\begin{cases} SOC_{\min} \le SOC \le SOC_{\max} = SOC_{r} \\ I_{rg} \le I_{rrg} \\ P_{ond} \le P_{rond} \end{cases} \tag{13}$$

Where: I_{rrg} is the nominal current of the designed regulators (A), P_{rond} is the nominal power of the inverter (W).

5.2. Presentation of the site

The previously presented methodology was applied using the solar radiation, temperature and the wind speed, collected for eight month on the site of Gandon (16.45° of longitude West, 15.96° of latitude North and 5 m of altitude) located in the Northwestern coast of Senegal. This region is characterized by a wind potential [24-26] well adapted to small wind turbines (about 0. 2 kW to 10 kW) on the one side and on the other side, this region is characterized by a very sunny weather [27] that can be used to produce energy with the use of PV modules.

Fig.3 gives the real and the theoretical distribution of Weibull. Fig.4 shows the hourly radiation for a typical day on the site of Potou.

5.3. Load profiles

The used load profile is typical of a village which water is salty, so it needs to be pumped and desalinated to have fresh water. So, the principal element of the used load profile is the desalination water system. It can be observed from Fig.5 that the power varies slightly between 5 a.m. and 5 p.m. That period corresponds to the operation of water pumping and a desalination system, commercial refrigerators plus domestic equipment (domestic refrigerator, Television, radio, etc.). Also during that period, solar radiation is very high. The peak of the power demand observed during the night is due to the domestic equipment (lighting, refrigeration and television…etc.) and the desalination and water pumping system which operate during day-time and night-time. The total consumption of energy is 94 kWh/d.

5.4. The components characteristics

The specifications of the components used to design and to optimize the hybrid PV/wind/diesel/Battery are presented in Table 1. Table 2 depicts three types of diesel generators which will be used to study the influence of diesel generator change on optimal configuration.

Table 1. Specifications of the wind turbine, PV module, regulator, battery and inverter

Type of devices	Specification
Wind turbine	
Cut-in wind speed Vci (m/s)	2.5
Rate wind speed Vr (m/s)	14
Cut-off wind speed Vco (m/s)	25
Rated power Pr (W)	5600
Output voltage (V)	48
Cost (€)	8870
PV module	
Rate voltage (V)	12
Nominal peak powerk (W)	150
Current of short-circuit ¶(A)	8.4
Voltage of open circuit (V)	21.6
Fill factor	0.74
Cost (€)	900
Battery	y
Nominal capacity (Ah)	200
Nominal voltage (V)	12
Cost (€)	416
Regulator	
Nominal current (A)	30
Nominal voltage (V)	48
Cost (€)	230
Inverter	1
Nominal Power (W)	3500
Nominal voltage (V)	48
Cost (€)	2799

Table 2. Specifications of the diesel generators

Type of diesel generator	Nominal output power (W)	Cost (€)
1	3050	668
2	4000	862
3	4600	879

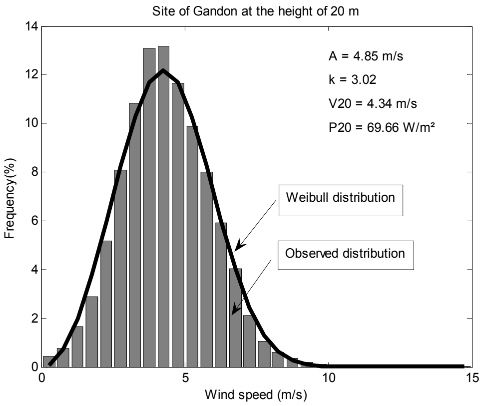

Fig.3. Real distribution and Weibull distribution on the site of Potou

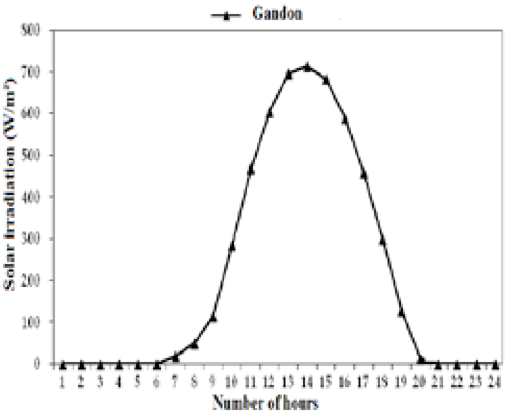

Fig.4. Profile of irradiation on the site of Potou

6. Results and discussions

The sizing of optimal hybrid PV/wind/diesel generator/battery systems was achieved using Multi-Objectives Genetic Algorithm approach. Results appear as an optimal Pareto front. Each solution of the best Pareto front was formed by a combination of hybrid systems and control strategy. The Levelized Cost of Energy and the CO_2 emission were computed for each combination.

Fig.6 shows the optimal Pareto front between the Levelized Cost of Energy (LCE) and the CO_2 emission. This optimal Pareto front corresponds to the use of the diesel generator number 3 (DG3).

It can be noted that the increasing of LCE implies the decreasing of the CO_2 emission. From Fig.6, three solutions (A, B, C) on the optimal Pareto front curve were used to illustrate the results.

Table 3 gives the size of devices, the output energy and the excess energy of the three selected solutions (A,B,C). It can be noted that the LCE decreases by 38% and 54% while passing from the solution A to the solutions B and C respectively. That because of the diminution of the components numbers of system, specially the wind turbines and the battery bank, in systems. In the contrast, the size of the diesel generator increases and it was more and more solicited. So, the operation hours increases. For example, the operations hours of the diesel generators pass from 4h/year to 70h/year and 980h/year when the solution passes from A to B and to C respectively. Thus, the CO_2 emission increases by 879.84 kgCO_2/year and by 3635.34 kgCO_2/year respectively when the solutions pass to B and to C from A.

From Table 3, it can be noted that the excess of energy was high (48 %) for the solution A. that due to the size of the hybrid system components used to supply the demand specially the wind turns and the battery bank. However the diesel generator was used for only 4h/year. So, the CO_2 emission was lower (6.66 kgCO_2/year). For the solution B and C, the excess of energy was lower (30 and 19 %). The lower value of the excess of energy for the solution B and C explains the adequate energy produced to meet the demand. For these two solution (B and C), CO_2 emission was 886.54 kgCO_2/year and 3642.00 kgCO_2/year. For the three solutions (A, B and C), the battery bank was rarely used. It is less used for the solution A. The average state of charge for this solution (A) was 88.99 %. However, this battery bank discharge deeply (up to 50 % of the nominal capacity) compared to the solution B and C which the minimum stat of charge was 60% (Table 3). Fig. 7 gives the average state of charge (SOC) of the battery bank. It can be seen that the SOC remain between SOC_{max} (100%) and the SOC_{min} (40%). The minimum SOC of systems was 60 %.

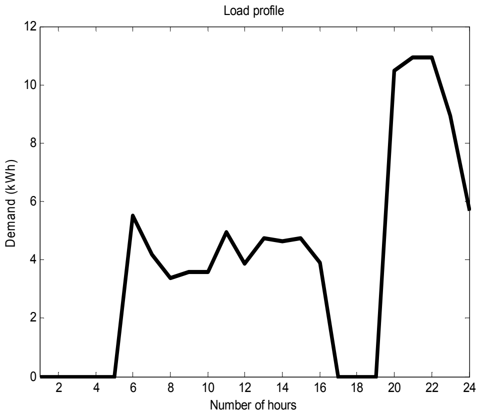

Fig.5. load profile of the demand

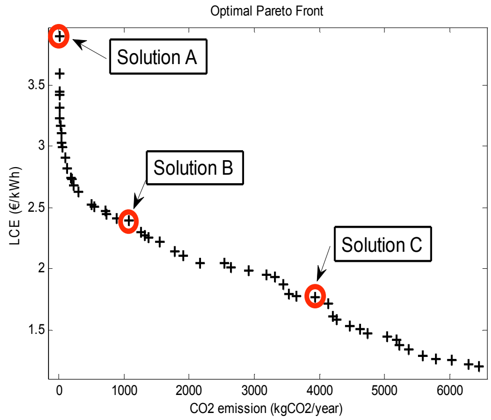

Fig.6. Optimal Pareto front

Table 3. Three solutions of the optimal Pareto front

Solution	Solution A	Solution B	Solution C
Number of PV modules	76	88	56
Number of Wind turbines	16	6	0
Number of Batteries	240	204	180
Number of Regulators	3	4	3
Number of Inverters	6	6	6
Number Diesel generators	1	8	11
Annual electrical energy delivered by PV generator (kWh/year)	20,561.00	23,808.00	17,150.00
Annual electrical energy delivered by wind turbine (kWh/year)	12,753.60	4,782.60	0.00
Annual electrical energy delivered by diesel generator (kWh/year)	5.26	676.69	9752.20
Annual operating hours of diesel (h/year)	4	70	980
Annual excess of energy (%)	48	30	19
SCO_{min} (%)	50	60	60
Mean of SCO (%)	88.99	77.60	83.76
Annualized cost system of energy (€/kWh)	3.89	2.41	1.77
CO2 emission (kg CO2/year)	6.66	886.50	3642.00

In order to highlight the influence of the type of diesel generators on the optimal configuration, three different diesel generators (Table 2) were used. Results of the optimization are given by Fig. 8 and appear as the optimal Pareto front. It can be seen that the three optimal Pareto front have the same profile. To illustrate clearly the difference between obtained results using the three size of diesel generators, the solution B (with DG3) from previously presented was selected with another solution corresponding to the use of the diesel generator N°1 (DG1) and the diesel generator N°2 (DG2) which are near to the solution B (see the Fig.8). Results corresponding to these solutions are given in the Table 4. It can be noted, from that table, the solution with DG2 and DG3 have the same components of system with eight diesel generators of type DG3 was selected for the solution DG3. The output energy from renewable energy was same (28,590.60 kWh/year) for the twos solution (DG2 and DG3). The diesel generator 3 operates for more time (70h) than diesel generator 2 (69h). The corresponding output energy from the diesel generaotr was 657.00 kWh/year for the DG2 and 676, 69 kWh/year for DG3.

For the solution with DG1, the configuration solicited more PV module and Battery bank than the wind turbine and the diesel generator. So, the selected diesel generator for that solution operates only for the 31h/year, while the DG2 and DG3 operate, respectively, for 69 and 70h/year. The CO_2 emission was 496.55 $kgCO_2$/year for DG1, 872.99 $kgCO_2$/year for DG2 and 886.50 $kgCO_2$/year for DG3.

The cost of energy decreases by 5.45 % and by 5.30 when passing from the solution DG1 to the solution DG2 and the solution DG3.

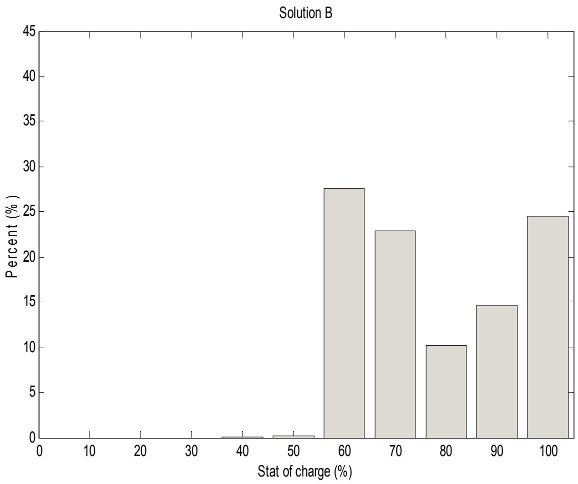

Fig.7. State of charge of the battery bank (solution B

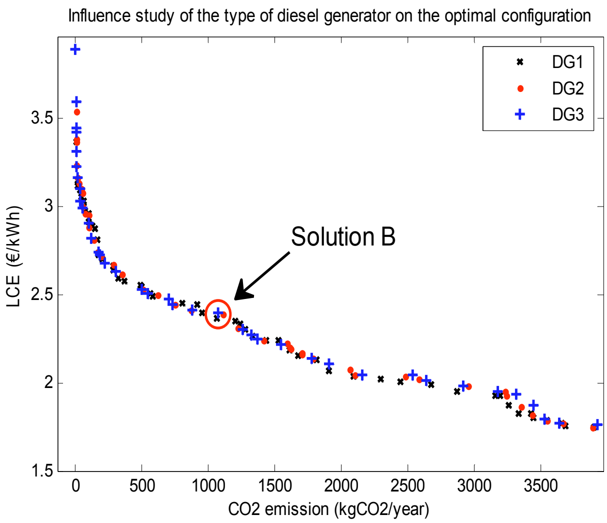

Fig.8. Optimal Pareto front with the use of diesel generators DG1, DG2 and DG3

Table 4. Solutions of the optimal Pareto front with the use of the diesel generators DG1, DG2 and DG3

Solution	DG1	DG2	DG3
Number of PV modules	96	88	88
Number of Wind turbines	5	6	6
Number of Batteries	224	204	204
Number of Regulators	6	4	4
Number of Inverters	6	6	6
Number Diesel generators	7	7	8
Annual electrical energy delivered by PV generator (kWh/year)	25,972	23,808	23,808
Annual electrical energy delivered by wind turbine (kWh/year)	3,985.50	4,782.6	4,782.6
Annual electrical energy delivered by diesel generator (kWh/year)	320,63	657.00	676,69
Annual operating hours of diesel (h/year)	31	69	70
Annual excess of energy (%)	35	30	30
SCO_{min} (%)	60	60	60
Mean of SCO (%)	78.64	77.58	77.60
Annualized cost system of energy (€/kWh)	2.552	2.413	2.417
CO2 emission (kg CO2/year)	496.55	872.99	886.50

7. Conclusion

A methodology to size an optimal stand-alone hybrid PV/wind/diesel/battery bank using a Multi-Objective Genetic Algorithm was developed in this paper. The developed methodology was applied on the site of Gandon to size hybrid PV/wind/diesel/battery systems minimizing the Levelized Cost of Energy (LCE) and the CO_2 emission. The collected solar radiation, temperature and wind speed data in the site of Gandon was used in this study. The application of the methodology has allowed determining several solutions which are presented under form optimal Pareto front.

Results have allowed outlining the following points:

- ✓ The increasing of the LCE implies the decreasing of the CO_2 emission.
- ✓ The LCE decreases by 38% and 54% while passing from the solution A to the solutions B and C respectively. In the contrast the CO_2 emission increases by 879.84 kgCO_2/year and by 3635.34 kgCO_2/year respectively when the solutions pass to B and to C from A.
- ✓ Battery bank was less solicited for the application on the site of Gandon, the minimum average state of charge was 77.58 % observed for the solution with the diesel generator DG2.
- ✓ The use of the diesel generator has an influence on the optimal configuration, so it is necessary to take into account of the type of diesel generator to choice the best device to minimize the cost of system and the CO_2 emission.

It would be interesting to perform modeling, incorporating the objectives of availability and reliability constraints of components to achieve a more accurate assessment of the cost of ownership system.

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